Scattering of He^3 from He^4†

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Doubly charged He^3 ions have been scattered from helium gas to permit the investigation of excited states in Be^7 at excitation energies between 3.9 and 8.4 MeV. In addition to the known $7/2^-$ level at 4.54 MeV, the $5/2^-$ member of this $l=3$ spin-orbit doublet has also been observed. This new state is located at an excitation energy of 6.51 ± 0.04 MeV and has a reduced width of 3.96×10^{-13} MeV cm. No positive-parity states are observed in this range of excitation energies. A phase-shift analysis of the data has been made for bombarding energies above 5.75 MeV, and the spin polarization of the scattered particles has been calculated. Several regions in the $\theta_{c.m.}$, E_{He^3} plane were found that should yield polarizations near unity.

INTRODUCTION

THE level structure of Li^7 and Be^7 has been predicted theoretically from a number of nuclear models. The predictions made on the basis of the shell,[1–3] cluster,[4–6] and rotational[7,8] models are essentially the same for the lowest states: $^2P_{3/2}$, $^2P_{1/2}$, $^2F_{7/2}$, and $^2F_{5/2}$. The first three of these have been known for some time, and a $5/2^-$ level is seen at an excitation somewhat above the $^2F_{7/2}$ level (at 7.18 MeV in Be^7 and at 7.47 MeV in Li^7). The energy separation of the $7/2^-$ state and this $5/2^-$ state is, however, much too great to be explained by the theoretical calculations. This discrepancy was partially removed when more detailed study of the $5/2^-$ state indicated that it corresponded to a $^4P_{5/2}$ configuration,[9–12] an assignment that was found to be in good agreement with theoretical predictions.[2] The resolution of this problem and the success of the predictions for the other excited states has made the apparent absence of the $^2F_{5/2}$ state quite disturbing.[7,13] Evidence for the presence of this state in Li^7 at ~6.6 MeV has been obtained from an analysis of the intensities of proton groups from the $Li^7(p,p')Li^{7*}$ reaction.[10] Its presence in Be^7 is confirmed by the present work.

The existence of a positive-parity state at ~6.5 MeV has also been suspected,[14–16] though much of the evidence is contradictory. The strongest evidence against such a state in this energy region is provided by the following observations:

(1) The $Li^6(p,\gamma)Be^7$ reaction is not resonant in this energy range and shows no indication of $E1$ capture.[17]

(2) This state is not seen in a careful study of the $Li^6(p,p)Li^6$ reaction, in which it was found possible below $E_p=1.5$ MeV to analyze the scattering data and data from the $Li^6(p,\alpha)He^3$ reaction on the basis that the only resonance nearby was the $^4P_{5/2}$ level.[18] Extension of the analysis to higher energies ($E_p\leq3$ MeV) indicated that a $1/2^+$ level may lie above the $^4P_{5/2}$ state. A level above the $^4P_{5/2}$ state has recently been observed directly by Whitehead and Harrison by extending the $Li^6(p,p)Li^6$ data to still higher energies. On the basis of a preliminary analysis, this level appears to have $l=1$. The reduced width for alpha-particle emission is small, and the reduced width for proton emission is large and agrees well with that of the $^4P_{5/2}$ level.[19] These tentative observations would thus favor the assignment of this level as belonging to the ^4P configuration, rather than as the state of positive parity proposed by McCray.

(3) No positive-parity states with appreciable alpha-particle width were observed in the range of excitation energies covered by the present work.

A summary of present knowledge concerning the level structure of Be^7 is given in Fig. 1.

EXPERIMENTAL

The doubly charged He^3 beam from the ONR-tandem accelerator was scattered from a He^4 target in a small volume, gas scattering chamber. The target gas was isolated from the high-vacuum system by a 2500-Å nickel foil before the beam collimator and by a 10 000-Å nickel foil in front of the Faraday cup. The scattered He^3 particles and recoil alpha particles were detected with two collimated counters employing solid-state

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detectors. The angular position of one counter was varied, while the other was fixed at a laboratory scattering angle of 30° as a monitor. The angular resolution of the variable counter was ±1°. This experimental apparatus and the techniques involved have been described recently in connection with the scattering of alpha particles from helium[20] and will be discussed here only where they differ from that description. The energy scale given has an estimated precision of ±15 keV, and the differential cross sections have an rms uncertainty of ±5%, excluding that error due to the statistical uncertainty. The range of the statistical uncertainty at each angle, for energies above 5.75 MeV, is given in Table I.

The elastic scattering of He^3 from He^4 has been studied previously for bombarding energies between 2.5 and 5.7 MeV by Miller and Phillips[21] and by Jones *et al.*[22] These experiments have studied the $^2F_{7/2}$ level in detail, and the spin polarization of the scattered He^3 particles was calculated from the derived phase shifts.[23]

TABLE I. Variation in the statistical uncertainty for bombarding energies above 5.75 MeV.

$\theta_{c.m.}$	Statistical uncertainty (%)
54.7°	1–1.5
63.4°	2–3
70.1°	2–4
73.7°	2–2.5
90.0°	2–3
98.4°	1.5–3
106.6°	1.5–4
116.8°	1.5–5

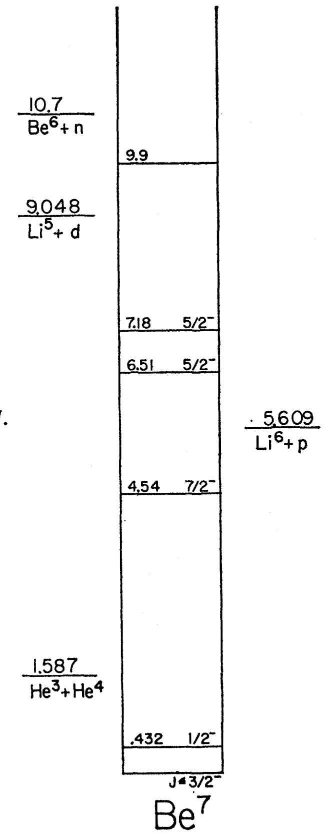

FIG. 1. Level diagram for Be^7.

The present work overlaps and is in agreement with those experiments in the energy region around the $^2F_{7/2}$ level. Above 5.75 MeV, the present data consist of eight excitation curves at center-of-mass angles 54.7°, 63.4°,

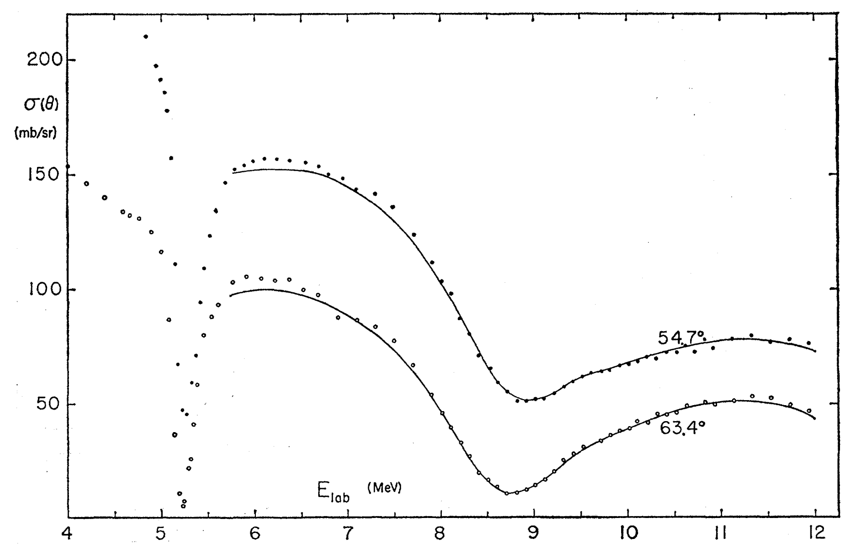

FIG. 2. Excitation curves for He^4-(He^3,He^3)He^4 at center-of-mass angles 54.7° and 63.4°. The differential cross section is in the center-of-mass system and is in units of millibarns per steradian. The solid lines represent the fit to the data given by the derived phase shifts that are shown in Fig. 9.

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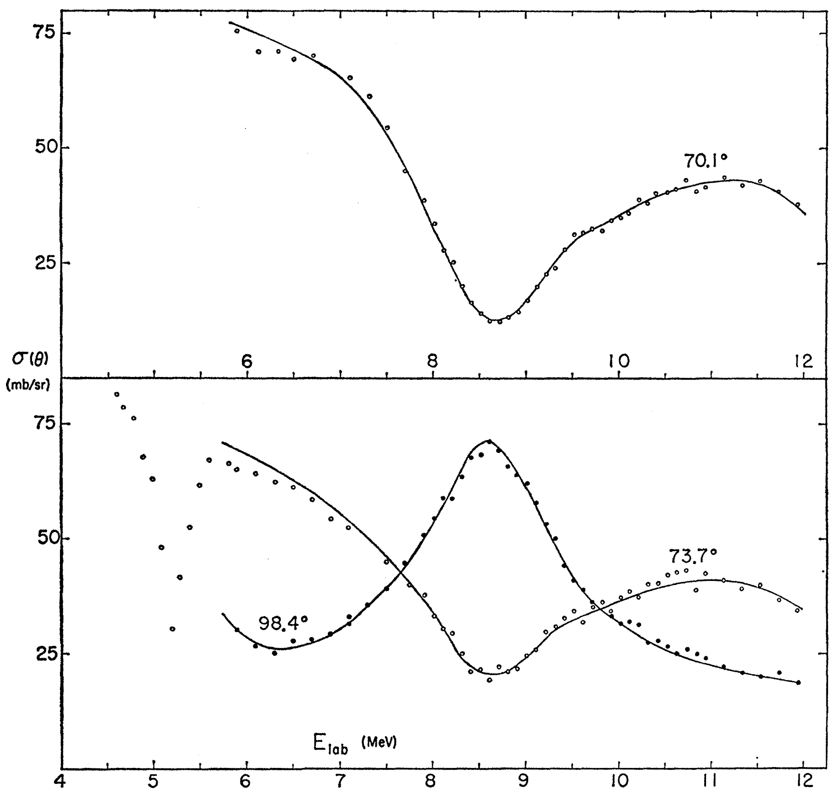

FIG. 3. Excitation curves for $He^4(He^3,He^3)He^4$ at center-of-mass angles 70.1°, 73.7°, and 98.4°. The symbols and units are the same as those of Fig. 2.

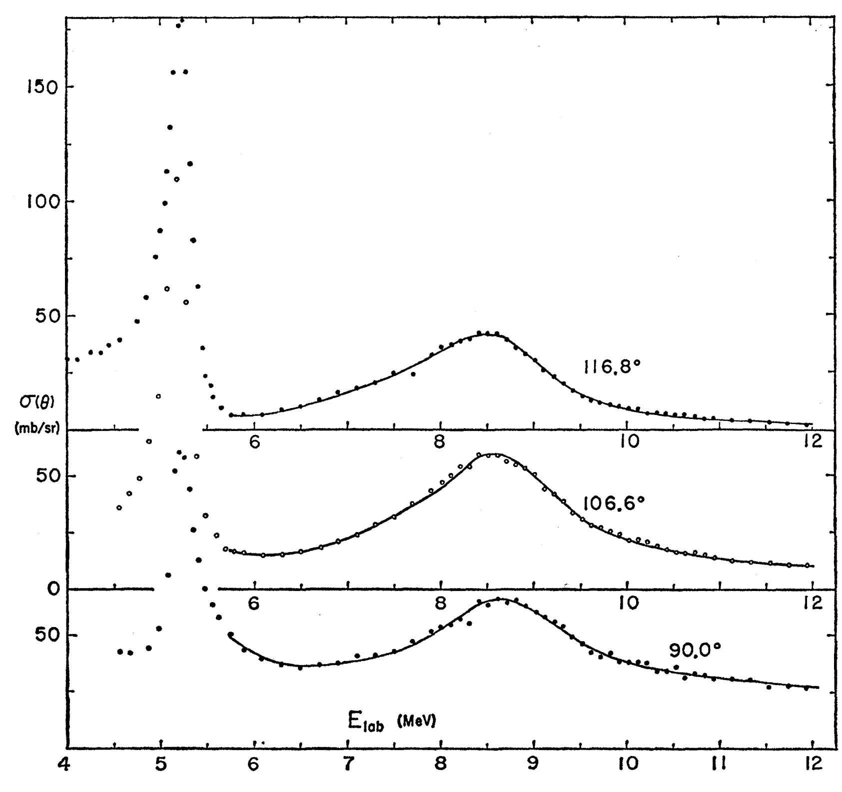

FIG. 4. Excitation curves for $He^4(He^3,He^3)He^4$ at center-of-mass angles 90.0°, 106.6°, and 116.8°. The symbols and units are the same as those of Fig. 2.

70.1°, 73.7°, 90°, 98.4°, 106.6°, and 116.8° and four angular distributions at bombarding energies of 6.25, 8.72, 9.69, and 11.94 MeV. In addition, excitation curves at laboratory angles of 20° and 30° were measured for $He^4(He^3,p)Li^6$ for bombarding energies above 8 MeV. The experimental data are summarized in Figs. 2–7.

The excitation curves given in Figs. 2–4 show the pronounced anomaly produced by the $7/2^-$ resonance for bombarding energies near 5.2 MeV. This resonance appears as a dip in the excitation function for the forward scattering angles shown and as a peak for the more backward angles. Also in evidence is another structure near 8.7 MeV which corresponds to the new resonance for which the assignment $J^\pi = 5/2^-$ is proposed. The identification of this new resonance as coming through the $l=3$ partial wave is obvious in view of the almost exact correlation of its energy variation at each angle with that of the $7/2^-$ level. That this structure cannot be due to a $3/2^+$ state is established by the pronounced dip in the excitation curve taken at 54.7°, a zero of $P_2(\cos\theta)$.

It is interesting that though the ${}^2F_{7/2}$ and ${}^2F_{5/2}$ states are clearly shown at all angles, no evidence of the ${}^4P_{5/2}$ state is observed in the elastic scattering. This state would occur at a He^3 bombarding energy of 9.8 MeV. Its presence at that energy, however, is confirmed in the yield curves for the $He^4(He^3,p)Li^6$ reaction shown in Fig. 7.

The rotational model of Li^7 of Chesterfield and Spicer[8] makes the prediction that a narrow $3/2^-$ level should exist at an excitation energy of $\sim$5.5 MeV. This is the only model that makes this prediction, and the existence of this state would thus serve as a unique test of its validity. The range of excitation energies between 5.05 and 5.65 was studied at $\theta_{\text{c.m.}} = 90°$ in 4-keV energy increments. This angle was chosen because there a P-wave resonance should appear as a large peak above the nonresonant background. Since this state was predicted to have much the same characteristics as the ${}^4P_{5/2}$ level, which we were unable to observe in the elastic scattering due to the competition of the open proton channel, there was no point in looking for the proposed $3/2^-$ level significantly above the threshold energy of 5.61 MeV. At excitation energies below 5 MeV, the large variations in the cross section due to the ${}^2F_{7/2}$ state would have obscured the presence of a narrow level. The choice of the energy increment corresponds to the calculated energy spread of the beam at the center of the target volume. No evidence for this level was observed, and calculations for center-of-mass energy spreads of the beam between 2 and 9 keV indicate that the width of this level in the center-of-mass system would have to be less than 1 keV to have been missed by this search.

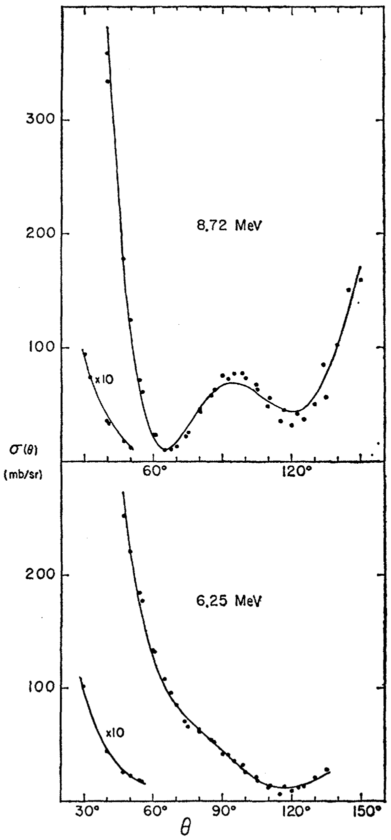

FIG. 5. Angular distributions for $He^4(He^3,He^3)He^4$ at laboratory bombarding energies of 6.25 and 8.72 MeV. The differential cross section and scattering angle are in the center-of-mass system. The cross section is in units of millibarns per steradian. The solid lines represent the fit to the data given by the derived phase shifts that are summarized in Table II.

THE PHASE-SHIFT ANALYSIS

The formula for the differential cross section for the elastic scattering of spin-1/2 particles from a spin-zero target has been given previously by Critchfield and Dodder.[24]

$$\sigma(\theta) = |f_c|^2 + |f_i|^2,$$

where

$$f_c(\theta) = -\frac{\eta}{2k}\csc^2\left(\frac{\theta}{2}\right)\exp\left[i\eta\ln\csc^2\left(\frac{\theta}{2}\right)\right] + \frac{1}{k}\sum_{l=0}^{\infty} e^{2i\alpha_l}P_l(\cos\theta)\left[(l+1)e^{i\delta_l^+}\sin\delta_l^+ + le^{i\delta_l^-}\sin\delta_l^-\right]$$

and

$$f_i(\theta) = \frac{1}{k}\sum_{l=1}^{\infty} e^{2i\alpha_l}\sin\theta\frac{dP_l(\cos\theta)}{d(\cos\theta)}\left[e^{i\delta_l^-}\sin\delta_l^- - e^{i\delta_l^+}\sin\delta_l^+\right].$$

In these expressions θ is the center-of-mass scattering angle, k is the wave number, $\eta = z_1z_2e^2/\hbar v$, and v is the relative velocity of the two particles. The phase shifts for total angular momentum $j=l+1/2$ and $j=l-1/2$ are denoted by δ_l^+ and δ_l^-, respectively. The α_l's are related to the usual Coulomb phase shifts, $\alpha_l = \sigma_l - \sigma_0$.

The spin polarization of the scattered particles may also be expressed in terms of the two amplitudes f_i and f_c.

$$\mathbf{P}(\theta) = \frac{-2\,\mathrm{Im}(f_cf_i^*)}{|f_c|^2 + |f_i|^2}(\hat{k}_{\text{in}} \times \hat{k}_{\text{out}}),$$

[24] C. L. Critchfield and D. C. Dodder, Phys. Rev. 76, 602 (1949).

where $\hat{k}_{in}$ and $\hat{k}_{out}$ are unit vectors in the direction of the incident and scattered beams, respectively. (Note that this convention is opposite to that adopted by Phillips and Miller.[23])

For bombarding energies above 7 MeV, this reaction can no longer be described in this simple way because of the opening of another channel, $He^4(He^3,p)Li^6$. The previous expressions, however, may be modified for use at higher energies by allowing the phase shifts to become complex.

$$e^{i\delta} \longrightarrow e^{i(\delta+i\nu)} = e^{-\nu}e^{i\delta} = (a)^{1/2}e^{i\delta}.$$

Thus, $e^{i\delta}\sin\delta$ becomes $ae^{i\delta}\sin\delta + i(1-a)/2$, and the total reaction cross section is given by

$$\sigma_R = \frac{\pi}{k^2}\sum_{l=0}^{\infty}\left[(2l+1)-(l+1)(a_l^+)^2 - l(a_l^-)^2\right].$$

To simplify the analysis, only a_0, a_2^-, and a_3^- were assumed to differ from unity. These correspond to the emission of S-wave protons with channel spins 1/2 and 3/2 and P-wave protons with total angular momentum 5/2.

Since extensive data were available for the $Li^6(p,\alpha)He^3$ reaction in this energy region,[18] these data were related to the $He^4(He^3,p)Li^6$ reaction by means of the reciprocity relations.[25] The value of a_3^- was calculated using the level parameters for the $^4P_{5/2}$ state that were obtained by McCray.[18] Assuming that $a_0 = a_2^-$, the variation of this remaining parameter was determined from the reaction cross section. This assumption, which corresponds to a statistical mixture for the channel spin states of the outgoing proton, is based on an analysis of the $Li^6(n,n)Li^6$ reaction reported by Willard.[26] These parameters are shown in Fig. 8. Since the values of a are all near unity, they have only a small effect on the analysis. This was verified when an attempt at analysis with all the a's equal to unity yielded essentially the same set of phase shifts as those given in this report.[27]

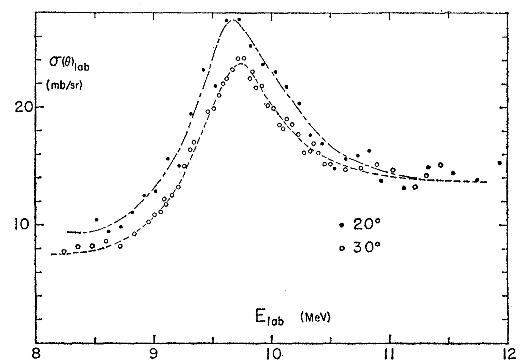

FIG. 7. Excitation curves for $He^4(He^3,p)Li^6$ reaction at laboratory scattering angles of 20° and 30°. The cross sections are in the laboratory system and are in units of millibarns per steradian. The broken lines serve only to connect the points.

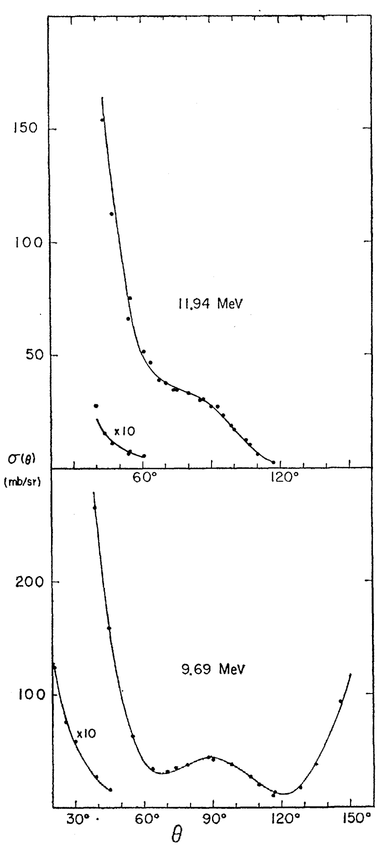

FIG. 6. Angular distributions for He^4-$(He^3,He^3)He^4$ at laboratory bombarding energies of 9.69 and 11.94 MeV. The units and symbols are the same as those of Fig. 5.

The analysis of the angular distribution at 6.25 MeV and the extrapolation of the phase shifts obtained by Miller and Phillips[21] were used to get trial phase shifts at the lowest energies. Smooth curves were drawn through the excitation curves, and eight-point angular distributions were generated at regular intervals. These angular distributions were then analyzed in the same manner as that described by Miller and Phillips.[21,28] Each phase shift was varied in 1° steps until a minimum value of

$$\chi^2 = \sum_{i=1}^{8}\left[\frac{\sigma_{\exp}(\theta_i)-\sigma_{\text{calc}}(\theta_i)}{\sigma_{\exp}(\theta_i)}\right]^2$$

was obtained. The data were analyzed several times, with a different order of variation for the first seven phase shifts being used each time. In general, the order made little difference, and the solution with the lowest value of χ^2 consistent with the over-all continuity of the curves was chosen.

Using these phase shifts as trial values, the angular distributions at 8.72, 9.69, and 11.94 MeV were an-

[25] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952), p. 530.

[26] H. B. Willard, J. K. Bair, J. D. Kington, and H. O. Cohn, Phys. Rev. **101**, 765 (1956).

[27] T. A. Tombrello, P. D. Parker, and C. A. Barnes, Bull. Am. Phys. Soc. **7**, 268 (1962).

[28] P. D. Miller and G. C. Phillips, Phys. Rev. **112**, 2043 (1958).

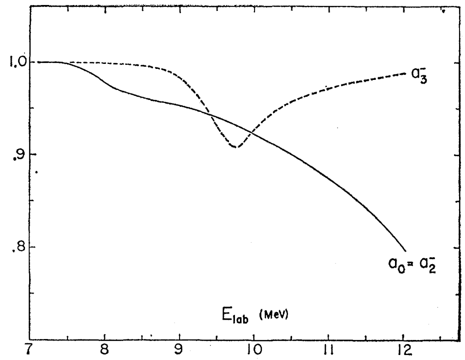

FIG. 8. The values of $a_0=a_2^-$ and a_3^- that were used in the analysis.

alyzed. The phase shifts derived from the four angular distributions are summarized in Table II, while those obtained from the smoothed excitation functions are shown in Fig. 9. The solid lines through the data points of Figs. 2–6 were calculated using these derived phase shifts.

In the energy range between 9 and 10 MeV, smaller steps were taken in the analysis to see if the δ_3^- phase shift would indicate the presence of the $5/2^-$ level at 7.18-MeV excitation. However, no sign of any anomalous behavior of δ_3^- was seen in this region. This is consistent with the level's small partial width for alpha-particle emission. That this partial width is, however, nonzero is evidenced by the peak in the $He^4(He^3,p)Li^6$ excitation curves in this energy region. The partial widths of the two $5/2^-$ levels will be discussed in more detail in the next section.

TABLE II. The phase shifts derived from the angular distributions.

	6.25 MeV	8.72 MeV	9.69 MeV	11.94 MeV
δ_0	−45°	−56°	−53°	−62°
δ_1^-	150°	129°	139°	140°
δ_1^+	140°	142°	139°	129°
δ_2^-	−24°	−13°	−1°	−15°
δ_2^+	−11°	−16°	−5°	−9°
δ_3^-	1°	88°	131°	144°
δ_3^+	166°	169°	181°	176°
a_0	1.00	0.958	0.935	0.805
a_2^-	1.00	0.958	0.935	0.805
a_3^-	1.00	0.993	0.910	0.986

RESONANCE PARAMETERS

Since the $^4P_{5/2}$ level seems to have an extremely small effect on the $He^3+\alpha$ elastic scattering, a single-level parameterization of δ_3^- was attempted.

$$\delta_3^- = -\tan^{-1}\left(\frac{F_3}{G_3}\right)_{\rho=kR} + \tan^{-1}\left[\frac{(k/A_3^2)\gamma_\lambda^2}{E_\lambda+\Delta_\lambda-E}\right]_{\rho=kR},$$

where

$$\Delta_\lambda = -\frac{\gamma_\lambda^2}{R}\left[\frac{1}{A_3^2}\left(F_3\frac{\partial F_3}{\partial\rho}+G_3\frac{\partial G_3}{\partial\rho}\right)+3\right]_{\rho=kR}$$

and

$$A_3^2=F_3^2+G_3^2.$$

E is the energy in the center-of-mass system, and F_3 and G_3 are the regular and irregular Coulomb wave functions. The nuclear radius is R, and γ_λ^2 is the reduced width. The necessary Coulomb functions were calculated on the Burroughs 220 computer.

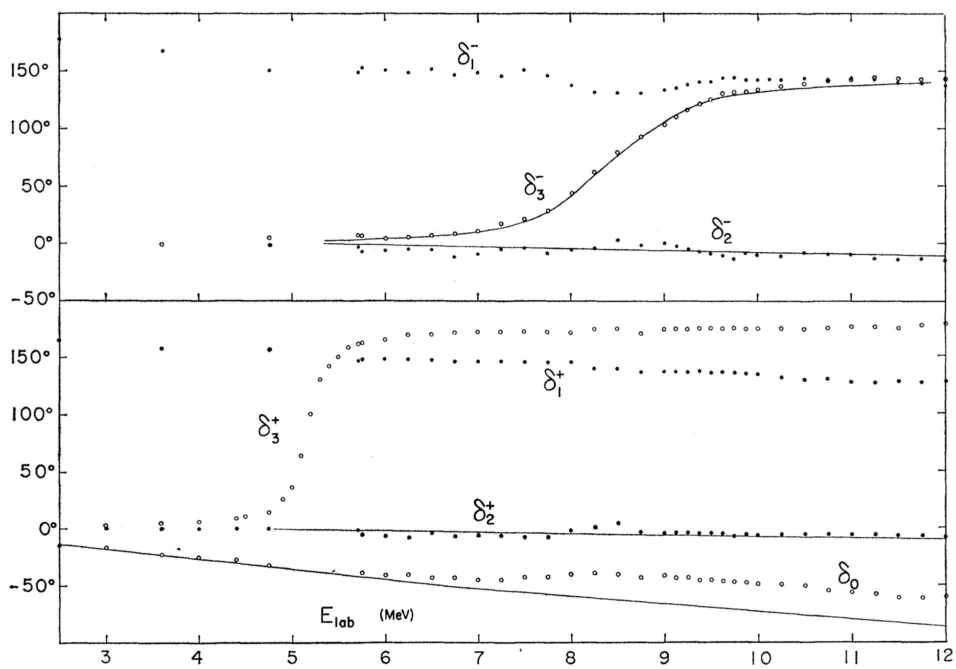

FIG. 9. The phase shifts derived from the smoothed excitation curves. The solid lines represent the single-level parameterizations of δ_0, δ_2^-, δ_2^+, and δ_3^-. The values plotted for energies below 5.75 MeV are those obtained from references 21 and 22.

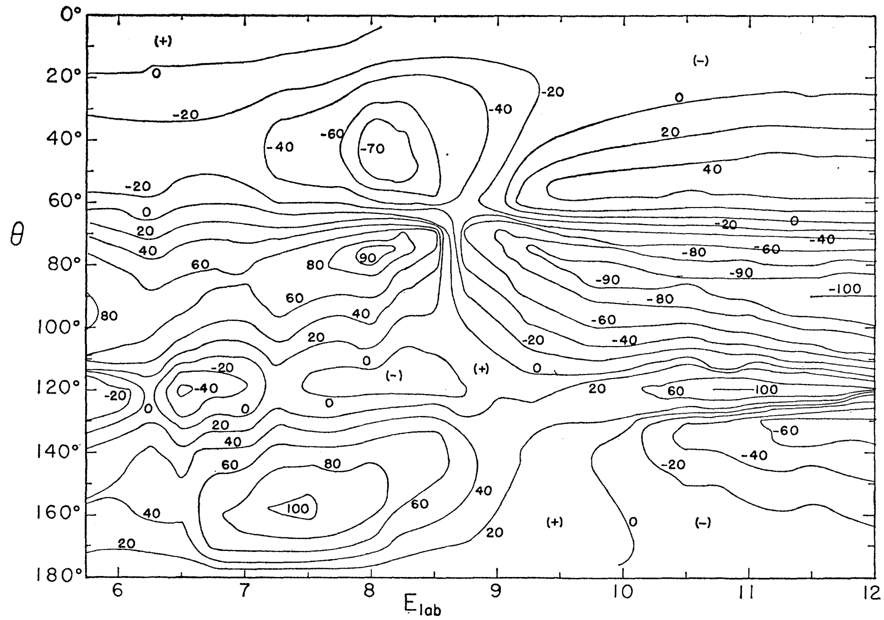

FIG. 10. A contour plot of the percent spin polarization (Basel convention) vs center-of-mass scattering angle and bombarding energy. These values of the polarization were calculated using the phase shifts shown in Fig. 9.

The parameters obtained were:

Nuclear radius, $R=4.4\times10^{-13}$ cm.
Reduced width, $\gamma_\lambda^2=3.96\times10^{-13}$ MeV cm.
Resonance energy, $E_{res}=8.60$ MeV.
Excitation energy, $E_x=6.51\pm0.04$ MeV.
Ratios to the Wigner limit, $\theta_\alpha^2=\gamma_\lambda^2/(3\hbar^2/2\mu R)=0.48$, and $\theta_p^2<0.02$.

The quantity μ is the reduced mass, and E_{res} is defined as that laboratory energy for which $E_\lambda+\Delta_\lambda-E$ goes to zero. The solid line fitting δ_3^- in Fig. 9 is that produced by this set of parameters. Values of the nuclear radius between 2.8×10^{-13} cm and 4.4×10^{-13} cm were investigated.

(1) No fit was possible at $R=2.8\times10^{-13}$ cm.
(2) A fair fit to δ_3^- was obtained using $R=3.5\times10^{-13}$ cm, but the value of θ_α^2 required was ~1.5.
(3) Values of the radius greater than 4×10^{-13} cm all produced good fits to the resonant phase shift. The final value of 4.4×10^{-13} cm was chosen, because it was the same as that taken by Miller and Phillips in parameterizing the $7/2^-$ level.

The limit on the value of θ_p^2 for proton emission from the $^2F_{5/2}$ level was obtained by assuming that it was responsible for the entire reaction cross section at the resonance energy. A summary of the level parameters for the $^2F_{7/2}$, $^2F_{5/2}$, and $^4P_{5/2}$ states is given in Table III. The value of θ_α^2 for the $^4P_{5/2}$ level given by McCray is consistent with that calculated on the basis of our reaction data.

TABLE III. Level parameters for the $^2F_{7/2}$, $^2F_{5/2}$, and $^4P_{5/2}$ states in Be^7.

Configuration	J^π	E_x (MeV)	R (cm)	θ_α^2	θ_p^2	Reference
$^2F_{7/2}$	$7/2^-$	4.54 ± 0.02	4.4×10^{-13}	0.36		21
$^2F_{5/2}$	$5/2^-$	6.51 ± 0.04	4.4×10^{-13}	0.48	<0.02	present work
$^4P_{5/2}$	$5/2^-$	7.18	4.1×10^{-13}	0.012	0.28	18

The solid lines shown for δ_0, δ_2^-, and δ_2^+ in Fig. 9 correspond to scattering from a charged hard-sphere of radius 2.8×10^{-13} cm. The two D-wave phase shifts agree with this description very well over the entire energy range, while the S-wave phase shift has this behavior below 6 MeV but tends to lie above the hard-sphere curve at higher energies. This deviation may result from an incomplete compensation for the reaction cross section or may be evidence for the $1/2^+$ level at higher energy that is suggested by McCray.[18]

SPIN POLARIZATION

The polarization of the scattered He^3 particles, calculated using the phase shifts shown in Fig. 9, is plotted versus the center-of-mass scattering angle and the He^3 bombarding energy in Fig. 10. The sign convention used is that adopted at the Basel Conference and is opposite to that of reference 23, which gives the polarization for this scattering reaction at lower energies.

The energy range between 9 and 12 MeV at $\theta=90°$ is seen to provide a nearly constant polarization that is near unity. This region and the corresponding region below the $^2F_{5/2}$ resonance at this angle should be useful in the analysis of He^3 polarization.

CONCLUSION

The lowest four levels of Be^7 predicted theoretically have all been found, and their ordering is in agreement with the theoretical predictions. The $^2F_{7/2}$ and $^2F_{5/2}$ states are found to have similar properties and have large reduced widths for the He^3+He^4 configuration and small reduced widths for the $p+Li^6$ configuration.

It is worthwhile to consider some of the questions that still need to be answered with regard to the level structure of Li^7 and Be^7.

(1) The separation of the ^2F states is calculated by most nuclear models to be about 1 MeV, while the observed separation is closer to 2 MeV. Shell-model calculations have indicated[12] that this discrepancy may be removed by allowing configuration mixing. Is it possible to allow sufficient mixing to fit the observed energy separation, while keeping small the ratio of the reduced width for the $p+Li^6$ configuration to that of the He^3+He^4 configuration? In connection with this point, does the fact that the two $5/2^-$ levels overlap strongly in energy but do not appear to mix appreciably indicate the presence of other "quantum numbers" which allow these states to remain almost orthogonal?

(2) These data together with the $Li^6(p,p)Li^6$ data of Whitehead indicate that above the $^4P_{5/2}$ level only one additional level is clearly visible below an excitation energy of 14 MeV. How can this be reconciled with the theoretical predictions that there should be a large number of possible levels in this energy range?

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Emission of Li^8, Be, and B Fragments from Nuclei in Photographic Emulsion

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A method of identification of tracks of heavy fragments emitted from highly excited nuclei in photographic emulsions exposed to 4.5-GeV negative pions is described. Charge spectra, energy spectra, angular distributions, etc., of the fragments are determined. An argument is presented for an isotropic emission of the fragments in the system of the moving parent Ag—or Br—nucleus.

INTRODUCTION

During the last few years extensive investigations of the emission of heavy fragments from high-energy nuclear disintegrations have been undertaken by various laboratories.[1–21]

The present paper deals with observations of lithium, beryllium, and boron fragments emitted from nuclear disintegrations produced by 4.5-GeV negative pions from the Berkeley Bevatron. The events were recorded in a stack of 200 stripped, electron sensitive Ilford G5 emulsions, each 10×15 cm and 600 μ thick. The pion beam entered the stack perpendicular to the 15-cm edge, and parallel to the plane of the emulsion, the intensity varying between 10^6–10^8 cm^{-2} perpendicular to the direction of the beam.

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